PREFACE

A goal of mine ever since becoming an educational researcher has been to help construct a sound theory to guide instructional practice. For far too long, educational practice has suffered because we have lacked firm instructional guidelines, which in my view should be based on sound psychological theory, which in turn should be based on sound neurological theory. In other words, teachers need to know how to teach and that "how-to-teach" should be based solidly on how people learn and how their brains function. As you will see in this book, my answer to the question of how people learn is that we all learn by spontaneously generating and testing ideas. Idea generating involves analogies and testing requires comparing predicted consequences with actual consequences. We learn this way because the brain is essentially an idea generating and testing machine. But there is more to it than this. The very process of generating and testing ideas results not only in the construction of ideas that work (i.e., the *learning* of useful declarative knowledge), but also in improved skill in learning (i.e., the *development* of improved procedural knowledge). Thus, to teach most effectively, teachers should allow their students to participate in the idea generation and testing process because doing so allows them to not only construct "connected" and useful declarative knowledge (where "connected" refers specifically to organized neuron hierarchies called outstars), but also to develop "learning-to-learn" skills (where "learning-to-learn" skills refer to general rules/guidelines that are likely located in the prefrontal cortex).

My interest in the neurological basis of instruction can be traced to a 1967 book written by my biologist father, the late Chester Lawson, titled *Brain Mechanisms and Human Learning* published by Houghton Mifflin. Although the book was written while I was still in high school, in subsequent years my father and I had many long conversations about brain structure and function, learning and development, and what it all meant for education. In fact, in that book, my father briefly outlined a theory of instruction that has subsequently been called the learning cycle. That instructional theory was put into practice by my father, by Robert Karplus and by others who worked on the Science Curriculum Improvement Study during the 1970s. My mathematician brother David Lawson has also boosted my interest in such issues. David worked on NASA's Space Station Program and is an expert in neural modeling. His help has been invaluable in sorting out the nuances of neural models and their educational implications.

Given this background, Chapter 1 begins by briefly exploring empiricism, innatism and constructivism as alternative explanations of learning. Empiricism claims learning results from the internalization of patterns that exist in the external world. Innatism claims that such patterns are internal in origin. Constructivism views learning as a process in which spontaneously generated ideas are tested through the derivation of expectations. The initial ideas are retained or rejected depending upon the extent that their expectations match future observations in an assumed-to-exist external world. Piaget's brand of constructivism with its theory of self-regulation is discussed as an explanation for development and learning. Piaget's self-regulation theory is based on biological analogies, largely on Waddington's theory of genetic assimilation. Genetic assimilation is described and used to explain psychological-level phenomena, specifically the development of proportional reasoning skill during adolescence. In spite of the value of self-regulation theory, an important theoretical weakness exists as the theory is based on biological analogies rather than on brain structure and function. Brain structure and function are discussed in Chapter 2 to hopefully eliminate this weakness.

Chapter 2 explains visual and auditory information processing in terms of basic brain structure and function. In brief, a hypothetico-predictive pattern is identified in both visual and auditory processing. Steven Grossberg's neural modeling principles of learning, perception, cognition, and motor control are presented as the basis for construction of a neurological model of sensory-motor problem solving. The pattern of problem solving is assumed to be universal, thus is sought in the higher-order shift from the child's use of an additive strategy to the adolescent's use of a proportions strategy to solve Suarez and Rhonheimer's Pouring Water Task. Neurological principles involved in this shift and in the psychological process of self-regulation are discussed, as are educational implications. The conclusion is drawn that reasoning is hypothetico-predictive in form because that is the way the brain works.

Many adolescents fail when attempting to solve descriptive concept construction tasks that include exemplars and non-exemplars of the concepts to be constructed. Chapter 3 describes an experiment that tested the hypothesis that failure is caused by lack of developmentally derived, hypothetico-predictive reasoning skill. To test this developmental hypothesis, individually administered training sessions presented a series of seven descriptive concept construction tasks to students (ages five to fourteen years). The sessions introduced the hypothetico-predictive reasoning pattern presumably needed to test task features. If the developmental hypothesis is correct, then the brief training should not be successful because developmental deficiencies in reasoning presumably cannot be remedied by brief training. Results revealed that none of the five and six-year-olds, approximately half of the seven-year-olds, and virtually all of the students eight years and older responded successfully to the brief training. Therefore, the results contradicted the developmental hypothesis, at least for students older than seven years. Previous research indicates that the brain's frontal lobes undergo a pronounced growth spurt from about four to seven years of age. In fact, performance of normal six-year-olds and adults with frontal lobe damage on tasks such as the Wisconsin Card Sorting Task, a task similar to the present descriptive concept construction tasks, has been found to be identical. Consequently, the present results support the hypothesis that the striking improvement in task performance found at age seven is linked to maturation of the frontal lobes. A neural network of the role the frontal lobes play in task performance is presented. The advance in reasoning that presumably results from effective operation of the frontal lobes is seen as a fundamental advance in intellectual development because it enables children to employ hypothetico-predictive reasoning to change their "minds" when confronted with contradictory evidence regarding features of perceptible objects, a reasoning pattern necessary for descriptive concept construction. Presumably, a further qualitative advance in intellectual development occurs when some students derive an analogous, but more advanced pattern of reasoning, and apply it to derive an effective problem-solving strategy to solve the descriptive concept construction tasks when training is not provided.

Chapter 4 describes an experiment testing the hypothesis that an early adolescent brain growth plateau and spurt influences the development of higher-level hypothetico-predictive reasoning skill and that the development of such reasoning skill influences one's ability to construct theoretical concepts. In theory, frontal lobe maturation during early adolescence allows for improvements in one's abilities to coordinate task-relevant information and inhibit task-irrelevant information, which along with both physical and social experience, influence the development of reasoning skill and one's ability to reject misconceptions and accept scientific conceptions. A sample of 210 students ages 13 to 16 years enrolled in four Korean secondary schools were administered four measures of frontal lobe activity, a test of reasoning skill, and a test of air-pressure concepts derived from kinetic-molecular theory. Fourteen lessons designed to teach the theoretical concepts were then taught. The concepts test was re-administered following instruction. As predicted, among the 13 and 14-year-olds, performance on the frontal lobe measures remained similar, or decreased. Performance then improved considerably among the 15 and 16-year-olds. Also as predicted, the measures of frontal lobe activity correlated highly with reasoning skill. In turn, prefrontal lobe function and reasoning skill predicted concept gains and posttest concept performance. A principal components analysis found two main components, which were interpreted as representing and inhibiting components. Theoretical concept construction was interpreted as a process involving both the representation of task-relevant information (i.e., constructing mental representations of new scientific concepts) and the inhibition of task-irrelevant information (i.e., the rejection of previously-acquired misconceptions).

Chapter 5 presents a model of creative and critical thinking in which people use analogical reasoning to link planes of thought and generate new ideas that are then tested by employing hypothetico-predictive reasoning. The chapter then extends the basic neural modeling principles introduced in Chapter 2 to provide a neural level explanation of why analogies play such a crucial role in science and why they greatly increase the rate of learning and can, in fact, make classroom learning and retention possible. In terms of memory, the key point is that lasting learning results when a match occurs between sensory input from new objects, events, or situations and past memory records of *similar* objects, events, or situations. When such a match occurs, an adaptive resonance is set up in which the synaptic strengths of neurons increase), thus a record of the new input is formed in longterm memory. Neuron systems called outstars and instars presumably enable this to occur. Analogies greatly facilitate learning and retention because they activate outstars (i.e., the cells that are sampling the to-be-learned pattern) and cause the neural activity to grow exponentially by forming feedback loops. This increased activity boosts synaptic strengths, thus causes storage and retention in long -term memory.

In Chapter 6, two hypotheses about theoretical concept construction, conceptual change and application are tested. College biology students classified at different levels of reasoning skill were first taught two theoretical concepts (molecular polarity and bonding) to explain the mixing of dye with water, but not with oil, when all three were shaken in a container. The students were then tested in a context in which they applied the concepts in an attempt to explain the gradual spread of blue dye in standing water. Next students were taught another theoretical concept (diffusion), with and without the use of physical analogies. They were retested to see which students acquired the concept of diffusion and which students changed from exclusive use of the polarity and bonding concepts (i.e., misconceptions) to the scientifically more appropriate use of the diffusion concept to explain the dye's gradual spread. As predicted, the experimental/analogy group scored significantly higher than the control group on a posttest question that required the definition of diffusion. Also as predicted, reasoning skill level was significantly related to a change from the application of the polarity and bonding concepts to the application of the diffusion concept to explain the dye's gradual spread. Thus, the results support the hypotheses that physical analogies are helpful in theoretical concept construction and that higher-order, hypothetico-predictive reasoning skill facilitates conceptual change and successful concept application.

Chapter 7 describes research aimed at testing the hypothesis that two general developmentally based levels of causal hypothesis-testing skill exist. The first hypothesized level (i.e., Level 4, which corresponds generally to Piaget's formal operational stage) presumably involves skill associated with testing causal hypotheses involving observable causal agents, while the second level (i.e., Level 5, which corresponds to a fifth, post-formal stage) presumably involves skill associated with testing causal hypotheses involving unobservable entities. To test this fifth-stage hypothesis, a hypothesis-testing skill test was developed and administered to a large sample of college students both at the start and at the end of a biology course in which several hypotheses at both causal levels were generated and tested. The predicted positive relationship between causal hypothesis-testing skill and performance on a transfer problem involving the test of a causal hypothesis involving unobservable entities was found. The predicted positive relationship between causal hypothesis-testing skill and course performance was also found.

Scientific concepts can be classified as descriptive (e.g., concepts such as predator and organism with directly observable exemplars) or theoretical (e.g., concepts such as atom and gene without directly observable exemplars). Understanding descriptive and theoretical concepts has been linked to students' developmental stages, presumably because the procedural knowledge structures (i.e., reasoning patterns) that define developmental stages are needed for concept construction. Chapter 8 describes research that extends prior theory and research by postulating the existence of an intermediate class of concepts called hypothetical (e.g., concepts such as subduction and evolution with exemplars that can not in practice be observed due to limits on the normal observational time frame). To test the hypothesis that three kinds of scientific concepts exist, we constructed and administered a test of the concepts introduced in a college biology course. As predicted, descriptive concept questions were significantly easier than hypothetical concept questions, than were theoretical concept questions. Further, because concept construction presumably depends in part on reasoning skill, students at differing reasoning skill levels (Levels 3, 4 and 5, where Level 5 is conceptualized as 'post-formal' in which hypotheses involving unseen entities can be tested) were predicted to vary in the extent to which they succeeded on the concepts test. As predicted, a significant relationship ($p < 0.001$) was found between conceptual knowledge and reasoning skill level. This result replicates previous research, therefore provides additional support for the hypothesis that procedural knowledge skills associated with intellectual development play an important role in declarative knowledge acquisition, i.e., in concept construction. The result also supports the hypothesis that intellectual development continues beyond the 'formal' stage during the college years, at least for some students.

Chapter 9 considers the nature of scientific discovery. In 1610, Galileo Galilei discovered Jupiter's moons with the aid of a new more powerful telescope of his invention. Analysis of his report reveals that his discovery involved the use of at least three cycles of hypothetico-predictive reasoning. Galileo first used hypothetico-predictive reasoning to generate and reject a fixed-star hypothesis. He then generated and rejected an *ad hoc* astronomers-made-a-mistake hypothesis. Finally, he generated, tested, and accepted a moon hypothesis. Galileo's reasoning is modeled in terms of Piaget's self-regulation theory, Grossberg's theory of neurological activity, Levine & Prueitt's neural network model and Kosslyn & Koenig's model of visual processing. Given that hypothetico-predictive reasoning has played a role in other important scientific discoveries, the question is asked whether it plays a role in *all* scientific discoveries. In other words, is hypothetico-predictive reasoning the essence of *the* scientific method? Possible alternative scientific methods, such as Baconian induction and combinatorial analysis, are explored and rejected as viable alternatives. The "logic" of scientific discovery and educational implications are discussed.

Instructional attempts to provoke preservice science teachers to reject nature-of-science (NOS) misconceptions and construct more appropriate NOS conceptions have been successful only for some. Chapter 10 describes a study that asked, why do some preservice teachers make substantial NOS gains, while others do not? Support was found for the hypothesis that making NOS gains as a consequence of instruction requires prior development of Stage 5 reasoning skill, which some preservice teachers lack. In theory, science is an enterprise in which scientists often use Stage 5 reasoning to test alternative hypotheses regarding unobservable theoretical entities. Thus, anyone lacking Stage 5 reasoning skill should be unable to assimilate this aspect of the nature of science and should be unable to reject previously constructed NOS misconceptions as a consequence of relatively brief instruction. As predicted, the study found the predicted positive relationship between reasoning skill (Levels 3, 4 and 5) and NOS

CHAPTER 1

HOW DO PEOPLE LEARN?

1. INTRODUCTION

Years ago while teaching junior high school math and science, two events occurred that made a lasting impression. The first occurred during an eighth grade math class. We had just completed a chapter on equivalent fractions and the students did extremely well on the chapter test. As I recall, the test average was close to 90%. The next chapter introduced proportions. Due to the students' considerable success on the previous chapter and due to the similarity of topics, I was dumbfounded when on this chapter test, the test average dropped below 50%. What could have caused such a huge drop in achievement? The second event occurred during a seventh grade science class. I cannot recall the exact topic, but I will never forget the student. I was asking the class a question about something that we had discussed only the day before. When I called on a red-haired boy named Tim, he was initially at a loss for words. So I rephrased the question and asked again. Again Tim was at a loss for words. This surprised me because the question and its answer seemed, to me at least, rather straightforward, and Tim was a bright student. So I pressed on. Again I rephrased the question. Surely, I thought, Tim would respond correctly. Tim did respond. But his response was not correct. So I gave him some additional hints and tried again. But this time before he could answer, tears welled up in his eyes and he started crying uncontrollably. I was shocked by his tears and needless to say, have never again been so persistent in putting a student on the spot. However, in my defence, I was so certain that I could get Tim to understand and respond correctly that it did not dawn on me that I would fail. What could have gone wrong?

Perhaps you, like me, have often been amazed when alert and reasonably bright students repeatedly do not understand what we tell them, in spite of having told them over and over again, often using what we believe to the most articulate and clear presentations possible, sometimes even with the best technological aids. If this sounds familiar, then this book is for you. The central pedagogical questions raised are these: Why does telling not work? Given that telling does not work, what does work? And given that we can find something that does work, why, in both psychological and neurological terms, does that something work? In short, the primary goal is to explicate a theory of development, learning and scientific discovery with implications for teaching mathematics and science. The theory will be grounded in what is currently known about brain structure and function. In a sense, the intent is to help teachers better understand effective teaching methods as well as provide both psychological and neurological level explanations for why those methods work.

We begin with a brief look at three alternative views of how people learn. This will be followed by a discussion of initial implications for higher-order cognition and for math and science instruction. Chapter 2 will introduce neural network theory with the intent of explaining learning in neurological terms. Subsequent chapters will expand on these and related ideas in the context of math and science instruction and in the context of scientific discovery.

2. EMPIRICISM, INNATISM AND CONSTRUCTIVISM

An early answer to the question of how people learn, known as *empiricism*, claims that knowledge is derived directly from sensory experience. Although there are alternative forms of empiricism espoused by philosophers such as Aristotle, Berkeley, Hume and Locke of Great Britain, and by Ernst Mach and the logical positivists of Austria, the critical point of the empiricist doctrine is that the ultimate source of knowledge is the external world. Thus, the essence of learning is the internalization of representations of the external world gained primarily through keen observation. *Innatism* in its various forms stands in stark opposition to empiricism. Innatism's basic claim is that knowledge comes from within. Plato, for example, argued for the existence of innate ideas that "unfold" with the passage of time. For a more modern innatist view see, for example, Chomsky and Foder (in Piattelli-Palerini, 1980). A third alternative, sometimes referred to as *constructivism*, argues that learning involves a complex interaction of the learner and the environment in which contradicted self-generated behaviors play a key role (cf., Piaget, 1971a; Von Glasersfeld, 1995; Fosnot, 1996).[1] What are we to make of these widely divergent positions? Consider the following examples.

Van Senden (in Hebb, 1949) reported research with congenitally blind adolescents who had gained sight following surgery. Initially these newly sighted adolescents could not visually distinguish a key from a book when both lay on a table in front of them. They were also unable to report seeing any difference between a square and a circle. Only after considerable experience with the objects, including touching and holding them, were they able to "see" the differences. In a related experiment, microelectrodes were inserted into a cat's brain (Von Foerster, 1984). The cat was then placed in a cage with a lever that dispensed food when pressed, but only when a tone of 1000 h2 was produced. In other words, to obtain food the cat had to press the lever while the tone was sounding. Initially the electrodes indicated no neural activity due to the tone. However, the cat eventually learned to press the lever at the correct time. And from that point on, the microelectrodes showed significant neural activity when the tone sounded.

---

[1] A philosophical examination of alternative forms of constructivism can be found in Matthews (1998). Discussion of some of these alternatives will be saved for Chapter 11. For now it suffices to say that the present account rejects extreme forms of constructivism that in turn reject or downplay the importance of the external world in knowledge acquisition.

In other words, the cat was "deaf" to the tone until the tone was of some consequence to the cat! In more general terms, it appears that a stimulus is not a stimulus unless some prior "mental structure" exists that allows its assimilation.

What about the innatist position? Consider another experiment with cats. In this experiment one group was reared in a normal environment. Not surprisingly, cells in the cats' brains became electrically active when the cats were shown objects with vertical lines. Another group was reared to the same age in an artificial environment that lacked vertical lines. Amazingly, the corresponding cells of these cats showed no comparable activity when they were shown identical objects. Thus, in this case at least, it would seem that the mere passage of time is not sufficient for the cat's brain cells to become "operational," i.e., for their mental structures to "unfold."

Next, consider a human infant learning to orient his bottle to suck milk. Jean Piaget made several observations of his son Laurent from seven to nine months of age. Piaget (1954, p. 31) reports as follows:

> From 0:7 (0) until 0:9 (4) Laurent is subjected to a series of tests, either before the meal or at any other time, to see if he can turn the bottle over and find the nipple when he does not see it. The experiment yields absolutely constant results; if Laurent sees the nipple he brings it to his mouth, but if he does not see it he makes no attempt to turn the bottle over. The object, therefore, has no reverse side or, to put it differently, it is not three-dimensional. Nevertheless Laurent expects to see the nipple appear and evidently in this hope he assiduously sucks the wrong end of the bottle.

Laurent's initial behavior consists of lifting and sucking whether the nipple is properly oriented or not. Apparently Laurent does not notice the difference between the bottom of the bottle and the top and/or he does not know how to modify his behaviour to account for presentation of the bottom. Thanks to his father, Laurent has a problem. Let's return to Piaget's experiment to see how the problem was solved.

On the sixth day when the bottom of the bottle is given to Laurent ".... he looks at it, sucks it (hence tries to suck glass!), rejects it, examines it again, sucks it again, etc., four or five times in succession" (p.127). Piaget then holds the bottle out in front of Laurent and allows him to simultaneously look at both ends. Laurent's glare oscillates between the bottle top and bottom. Nevertheless, when the bottom is again presented, he still tries to suck the wrong end. The bottom of the bottle is given to Laurent on the 11th, 17th, and 21st days of the experiment. Each time Laurent simply lifts and sucks the wrong end. But on the 30th day, Laurent "...no longer tries to suck the glass as before, but pushes the bottle away, crying" (p. 128). Interestingly, when the bottle is moved a little farther away, "...he looks at both ends very attentively and stops crying" (p. 128). Finally, two months and ten days after the start of the experiment when the bottom of the bottle is presented, Laurent is successful in first flipping it over as he "...immediately displaces the wrong end with a quick stroke of the hand, while *looking beforehand* in the direction of the nipple. He therefore obviously knows that the extremity he seeks is at the reverse end of the object" (pp. 163-164).

Lastly, consider a problem faced by my younger son when he was a 14-month old child playing with the toy shown in Figure 1. Typically he would pick up the cylinder

CHAPTER 2

THE NEUROLOGICAL BASIS OF SELF-REGULATION

1. INTRODUCTION

Chapter 1 argued that learning and development are constructive processes involving complex interactions within the maturing organism, its behaviors, and the environment. Piaget's theory of self-regulation explains much of what goes on during knowledge construction. However, as pointed out, Piaget's theory is based largely on evolutionary and developmental analogies, rather than on neural anatomy and physiology. Thus, the goal of the present chapter is to provide a more solid theoretical footing by exploring brain structure and function and their relationship to self-regulation. A considerable amount of progress has been made during the past 30 or so years in the related fields of neural physiology and neural modeling that allows us to begin to connect psychological phenomena with its neurological substrate. We begin with a discussion of how the brain processes visual input.

2. HOW DOES THE BRAIN PROCESS VISUAL INPUT?

How the brain spontaneously processes visual input is the most thoroughly researched and understood area of brain research. In general, that research aims to develop and test neural network models that have become known as parallel distributed processing or connectionist models. As reviewed by Kosslyn & Koenig (1995), the ability to visually recognize objects requires participation of the six major brain areas shown in Figure 1.

How do these six areas function to identify objects? First, sensory input from the eyes produces a pattern of electrical activity in an area referred to as the visual buffer, located in the occipital lobe at the back of the brain. This pattern of electrical activity produces a spatially organized image within the visual buffer (e.g., Daniel & Whitteridge, 1961; Tootell et al., 1982). Next, a smaller region within the occipital lobe, called the attention window, performs detailed processing (Possner, 1988; Treisman & Gelade, 1980; Treisman & Gormican, 1988). The activity pattern in the attention window is then simultaneously sent along two pathways on each side of the brain, one that runs down to the lower temporal lobe, and one that runs up to the parietal lobe. The lower temporal lobe, or ventral subsystem, analyses object properties, such as shape, color and texture, while the upper parietal lobe, or dorsal subsystem, analyses spatial properties, such as size and location (e.g., Desimone & Ungerleider, 1989; Farah, 1990; Haxby et al., 1991; Maunsell & Newsome, 1987; Ungerleider & Mishkin, 1982). Patterns of activity within the lower temporal lobe are matched to patterns stored in visual memory (e.g., Desimone et al., 1984; Desimone & Ungerleider, 1989; Miyashita & Chang, 1988). If a good match is found, the object is recognized. Otherwise, it is not. The dorsal subsystem of the parietal lobes encodes input used to guide movements such as those of the eyes or limbs. The neurons in that region fire just before movement, or register the consequences of movements (e.g., Andersen, 1987).

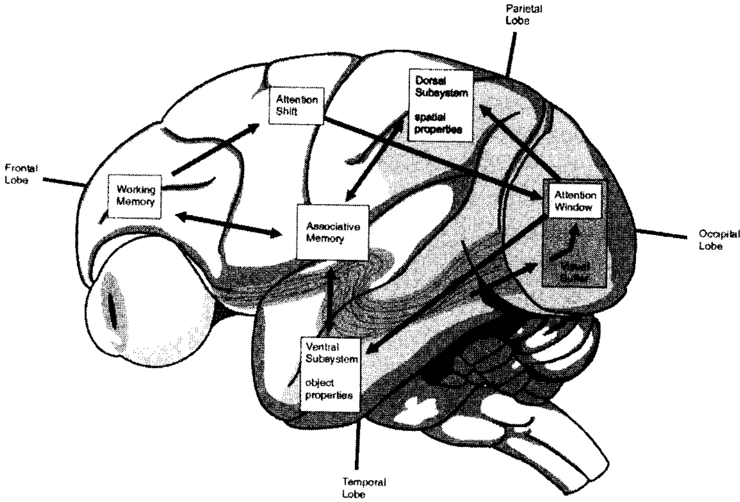

Figure 1. Brain areas involved in visual object recognition. Kosslyn & Koenig's model of the visual system consists of six major subsystems. The order in which information passes from one subsystem to the next is shown. The subsystems generate and test hypotheses about what is seen in the visual field.

Outputs from the ventral and dorsal subsystems come together in what Kosslyn and Koenig call associative memory. Associative memory is located primarily in the hippocampus, the limbic thalamus and the basal forebrain (Miskin, 1978; Miskin & Appenzeller, 1987). The ventral and dorsal subsystem outputs are matched to patterns stored in associative memory. If a good match between output from visual memory and the pattern in associative memory is obtained, then the observer knows the object's name, categories to which it belongs, sounds it makes and so on. But if a good match is not obtained, the object remains unrecognized and additional sensory input must be obtained.

Importantly, the search for additional sensory input is far from random. Rather, stored patterns are used to make a second hypothesis about what is being observed, and this hypothesis leads to new observations and to further encoding. In the words of

Kosslyn and Koenig, when additional input is sought, "One actively seeks new information that will bear on the hypothesis... The first step in this process is to look up relevant information in associative memory" (p. 57). Information search involves activity in the prefrontal lobes in an area referred to as working memory. Activating working memory causes an attention shift of the eyes to a location where an informative component *should be* located. Once attention is shifted, the new visual input is processed in turn. The new input is then matched to shape and spatial patterns stored in the ventral and dorsal subsystems and kept active in working memory. Again in Kosslyn & Koenig's words, "The matching shape and spatial properties may in fact correspond to the hypothesized part. If so, enough information may have accumulated in associative memory to identify the object. If not, this cycle is repeated until enough information has been gathered to identify the object or to reject the first hypothesis, formulate a new one, and test it" (p. 58).

For example, suppose Joe, who is extremely myopic, is rooting around the bathroom and spots one end of an object that appears to be a shampoo tube. In other words, the nature of the object and its location prompt the spontaneous generation of a shampoo-tube hypothesis. Based on this initial hypothesis, as well as knowledge of shampoo tubes stored in associative memory, when Joe looks at the other end of the object, he expects to find a cap. Thus he shifts his gaze to the other end. And upon seeing the expected cap, he concludes that the object is in fact a shampoo tube. Or suppose you observe what your brain tells you is a puddle of water in the road ahead. Thanks to connections in associative memory, you know that water is wet. Thus, when you continue driving, you expect that your tires will splash through the puddle and get wet. But upon reaching the puddle, it disappears and your tires stay dry. Therefore, your brain rejects the puddle hypothesis and generates another one, perhaps a mirage hypothesis. The pattern of information processing involved in these examples can be summarized as follows:

If... the object is a shampoo tube, (shampoo-tube hypothesis)
and... Joe looks at the other end of the object, (imagined test)
then... he should find a cap. (predicted result)
And... upon looking at the other end (actual test), he does find a cap. (observed result)
Therefore... the hypothesis is supported; the object is most likely a shampoo-tube. (conclusion)

And for the second example:

If... the object is a puddle of water, (puddle hypothesis)
and... you continue driving toward it, (imagined test)
then... your tires should splash through the puddle and they should get wet. (predicted result)
But... upon reaching the puddle (actual test), it disappears and your tires do not get wet. (observed result)

CHAPTER 3

BRAIN MATURATION, INTELLECTUAL DEVELOPMENT AND DESCRIPTIVE CONCEPT CONSTRUCTION

1. INTRODUCTION

Thus far we have found the pattern of hypothetico-predictive reasoning at work in our attempts to draw in a mirror, in the behavior of Piaget's son Laurent learning to orient his bottle to suck milk, in the case of the unlit barbecue, in both visual and auditory information processing, and in the solution of a proportions problem by adolescents. Is the same pattern at work in students' reasoning during descriptive concept construction? Consider for example the creatures called Mellinarks in the first row of Figure 7. Why do you suppose these are Mellinarks while the creatures in the second row are not Mellinarks? In other words, what makes a Mellinark a Mellinark? Can you use the information in the figure to find out? If so, which creatures in row three are Mellinarks? How do you know? In other words, how do you define a Mellinark and how did you arrive at that definition? What were the steps in your reasoning? Take a few minutes to try to answer these questions before reading on.

To gain insight into the reasoning used by students to solve the Mellinark Task, several students tried the task and told us about their reasoning. Consider, for example, the following remarks of a student who identified creatures one, two, and six in row three as Mellinarks (Lawson, McElrath, Burton, James, Doyle, Woodward, Kellerman & Snyder, 1991, p. 967):

> Number one, two, and six are Mellinarks.
>
> OK, how did you figure that out?
>
> Um. Well, the first thing I started looking for was just overall shape, whether it's straight, looks like a dumbbell, but this doesn't really work, because some of these (row two) are similar in overall body shape. So I ruled that out. Well, then I said, all of these are spotted (row one). But some of these (row two) are spotted and these aren't Mellinarks, so that can't be the only thing. So I looked back at these (row one) and noticed that they all have a tail. But some of these have a tail (row two), so that can't be the only thing either. And so then I was sort of confused and had to look back, and think about what else it was. Then I saw the big dot. So all of these (row one) have all three things, but none of these (row two) have all three.

According to the student, she first generated the idea that overall shape is a critical feature. But as she tells us, this idea was quickly rejected because some of the creatures in row two are similar in overall shape. Thus, at the outset, the student may have reasoned like this:

If...overall shape is a critical feature of Mellinarks, (descriptive hypothesis)
and...I look closely at the non-Mellinarks in row two, (behavioral test)
then...none should be similar in overall shape to the Mellinarks in row one. (prediction)
But...some of the non-Mellinarks in row two are similar in overall shape. (observed result)
Therefore..."I ruled that out," i.e., I concluded that my initial idea was wrong. (conclusion)

Of course this is the same pattern of reasoning that we have seen before. Some logicians call this pattern "reasoning to a contradiction" or "reductio absurdum" (e.g., Ambrose & Lazerowitz, 1948). And as we can see in the remainder of the student's comments, the pattern appears to have been recycled until all contradictions were eliminated. So after rejecting her initial descriptive hypothesis, the student seems to have quickly generated others (e.g., spots are the key feature, a tail is the key feature) and presumably tested them in the same fashion until she eventually found a combination of features (spots, tail, big dot) that led to predictions that were not contradicted, i.e.,

If...Mellinarks are creatures that have spots, a tail, and one big dot, (descriptive hypothesis)
and...I check out all the creatures in rows one and two, (test)
then...all those in row one should have all three "things" and none in row two should have all three "things." (prediction)
And...this is what I see. (observed result)
and six in row three have all three "things" so they are Mellinarks). (conclusion)

Did you also conclude that creatures one, two, and six of row three are Mellinarks? If so, did your reasoning look something like the above? How do you suppose a sample of high school students would do on a series of Mellinark-type tasks? Would they also use this reasoning pattern? Or would they use something else and run into difficulties? To find out, Lawson, et al. (1991) administered a series of Mellinark-type tasks to 314 high school students. Interestingly, not only did many students experience difficulties, their performance was highly correlated with performance on a measure of scientific and mathematical reasoning (i.e., developmental level).

Difficulties experienced by students who presumably failed to employ cycles of hypothetico-predictive reasoning to solve the tasks were exemplified by the following discussion with a student following her failed attempt:

Suppose I define a Mellinark as being a creature with a tail. How could I test that idea? Is there any information here that would tell me if that idea is right or wrong?

> *...Um...you could um...huh...a...just look to see if the other creatures have the same tails...or, I mean...you know...characteristics of the creatures...with the tails and the points and the dots and stuff to see if they are...you know...all the same or close to...and then...um...heh...I don't know...heh.*
>
> OK, let's look at the second row. We know that none of these are Mellinarks. So what would you expect about these with regard to tails? I mean, if it's true that Mellinarks are creatures with tails then what would you expect to find in row two with regard to tails?
>
> *Um...they would a...they would be some different kind of creature with tails...I don't know...they would um...I don't know...they would just...they don't have the dots on 'em. And then...um...they are more...I don't know.*
>
> OK. Let's go back. Once again, I'm going to say that Mellinarks are creatures with tails and I look down here (row two) and I see that this non-Mellinark has a tail. See that tail right there?
>
> *Yeah*
>
> And I know that is not a Mellinark. So I would conclude from that my definition must be wrong.
>
> *Yeah...well they could have classified 'em wrong. It could have been a mistake. These would have been up with the other Mellinarks.*

Although this sort of response and the quantitative data reported by Lawson et al. (1991) reveal clear difficulties by many high school students, a question remains as to the cause(s) of the difficulties. Perhaps the difficulties stem from students' lack of hypothetico-predictive reasoning skill. Suppose like Piaget (e.g., Piaget, 1964), we assume that such reasoning skill is the product of intellectual development (i.e., the product of physical and social experience, neural maturation and self-regulation). If this is true, then brief verbal training in the use of such reasoning should not be successful in provoking students to solve Mellinark-type tasks. In other words, the training should fail because, in theory, the necessary reasoning skill results from the long-term process of intellectual development, not from short-term training.

Consequently, research was initiated in which six Mellinark-type tasks were constructed and a brief verbal training session was used to point out potentially relevant features (i.e., provide descriptive hypotheses to be tested) and to explain to students how to use cycles of *If/then/Therefore* reasoning to test those features and solve the tasks. More specifically, the reasoning guiding the research can be stated as follows:

If...the difficulties experienced high school students are caused by lack developmentally derived, hypothetico-predictive reasoning skill needed to construct descriptive concepts, (developmental hypothesis)